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REPORT NO. 1182
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Department of the Army Project No. 503-04-002

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

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JMDewey/OTJohnson/JDPatterson,II/jk
Aberdeen Proving Ground, Md.
November 1962

MECHANICAL IMPULSE MEASUREMENTS CLOSE TO EXPLOSIVE CHARGES

ABSTRACT

A mechanical plug gage is used for measuring "face-on" impulse in air blast close to spherical Pentolite explosives detonated in air at different ambient pressures. The data are compared with previous results.

The study indicates that at small distances ($Z < 1.5$ ft/lb$^{1/3}$) the change in normally reflected impulse with variation in ambient pressure is negligible; it further suggests that the measured impulse, within several charge radii, of the explosive is due to the flow of the explosion gases and that the interchange of impulse between positive and negative phases is small.

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INTRODUCTION

The "flying plug" technique developed by Johnson, Olson, Patterson, and Williams[1,2] is an easy and precise method for measuring the impulse imposed upon a rigid wall by the normal incidence of an air shock. Its use for routine comparison of different explosives has brought out the importance of several anomalies now apparent in previous work, particularly the failure of Hopkinson scaling.[3] Moreover, the ambient pressures ranging between sea level and 100,500 ft altitude and scaled distances ($R/W^{1/3}$) from 0.5 to 2.0 ft/lb$^{1/3}$ used were not sufficient to distinguish between Sachs's scaling for ambient pressure and the absence of any effect of ambient pressure on normally reflected impulse. The present study was undertaken because a reliable estimate of the effect of altitude was required. The marked failure of Hopkinson scaling at the larger scaled distances ($Z > 1.5 < 3$ ft/lb$^{1/3}$) made necessary a detailed study of parameters affecting the results. Hopkinson scaling, which states only that both distances and times scale linearly with charge dimensions, appears to be a necessary consequence of the fundamemtal equations of adiabatic spherical fluid flow. It is later shown that measurements of first positive impulse scale correctly.

Measurements in this work extend to lower ambient pressures and to greater distances from the explosive charge than those previously published and show that normally reflected impulse close to the charge ($Z < 1.5$ ft/lb$^{1/3}$) reaches a limiting value as the ambient pressure is reduced, and that Sachs's scaling of impulse fails as does that of peak pressure. (The peak pressure ratio, P/P_o at the charge surface is independent of ambient pressure for instance.) Deviations are fortuitously small.

EQUIPMENT

The equipment used is a simplified form of that described previously.[1,2] In Table V, measurements on equipment of reference (2) are largely those obtained photographically. All other results not previously published are from measurements made electronically. The method for stopping the counter chronograph found most reliable and now used is a "make" circuit between a pair of springs located in the base of the enclosure within which the plug falls.

The magnetic plug support has been eliminated and the plug is supported by narrow strips of pressure-sensitive tape or aluminum foil. The tape separates from the plug with no measurable drag. These changes made it possible to substitute the screw-in adapter around the plug with an insert consisting of a one foot square plate with a flared hole in the center to accommodate the plug. This insert is simpler and much more readily replaced when damaged in the course of firings. Elimination of the camera not only greatly reduced the time to complete a measurement but permitted enclosure of the space, in which the plug travels, by a 12" diameter tube thus eliminating the effect of blast on the chronograph "stop" mechanism. A loose sleeve provides quick access to the contact springs. These changes have resulted in a simply constructed piece of equipment which is more readily movable. Moreover, results appear to be somewhat more reliable than when a camera was used, although the precision has not been improved.

Measurements for study of the equipment at sea level were made in the open; those at reduced ambient pressure were conducted in a controlled pressure cylinder 12 feet in diameter and 30 ft. long. The lowest ambient pressure condition attainable rapidly and reliably maintained was 20 mm of mercury which simulates an altitude of approximately 80,000 feet. Measurements at simulated altitudes of 100,000 and 125,000 feet and those at a scaled distance of 3 ft/lb$^{1/3}$ using charges weighing more than 1/8 pound were made in the 30-ft diameter blast sphere.[2]

STUDY OF PERFORMANCE OF EQUIPMENT

The increase in reflected impulse with charge weight, so apparent in reference (1) at a scaled distance of 2.5 feet per pound$^{1/3}$, appeared to some extent at all distances greater than 1 foot/pound$^{1/3}$ and even at 0.5 foot/pound$^{1/3}$. The obvious unknown reproducibly affecting the results is the time over which the impulse is measured. The compilation of data on spherical Pentolite by Goodman[5] shows agreement between plug and piezoelectric gage measurements of normally reflected impulse to within the precision of the measurements. This suggests that the published measurements are, at least approximately, those of positive impulse. An empirical test of this inference was therefore undertaken.

Tables I-III give results for charge weights of 1/8 to 1 pound at 0.5, 2.5 and 3.0 feet per pound$^{1/3}$. The plate previously employing the screw-in adapter was 1" thick, the plate with insert now in use is 3/4" thick. Thus when the surface of the plug has moved a relatively short distance, further acceleration, positive or negative, is small. If accurate impulse measurements are assumed, then at a given scaled distance the velocity of the plug varies only as the one-third power of the charge mass, but inversely as the plug mass. The time t_p given in Table II is approximately that for the plug to move through the plate thickness or length of tube attached to the back of the plate. It is apparent that, except at the smallest scaled distance, shortening the time for passage of the plug into free air behind the plate increases the impulse. Figure 1 shows this from the data of Table II. Presumably the negative phase of the blast decelerates the plug when this time of passage is long. Little is known directly of the duration of the various phases, except at the larger scaled distances ($Z > 5$ ft/lb$^{1/3}$) which Curtis[6] used. The results with a three-inch length of tube attached to the back of the plate, though of low precision, show that when the pressure on the top of the plug is maintained near that in the shock for more than a few milliseconds the reduction in impulse is large. This is in general agreement with the computations of Brode[7] for TNT and with the observations of Curtis[6] at larger distances from spherical Pentolite charges. The times required for a measurable effect of the negative phase are an order of magnitude longer than would be expected from piezoelectric gage measurements of positive duration. This may result from a large over-estimate of the time during blast is effective in accelerating the plug, from damping in the piezoelectric gages, or from both. Further study with improved instrumentation is needed to resolve such apparent disagreements.

In planning these experiments, it was anticipated that lengthening the time of measurement (duration of loading) would lead to a measure of total impulse, i.e., that a limiting value would be found at long times. While there is a suggestion of this in Table II, no minimum was found. A maximum scaled impulse, independent of plug and charge weight, is found with light plug or heavy charges. Agreement with Hopkinson scaling is found when the

TABLE I

Scaled Impulse, $I/W^{1/3}$ as a Function of Charge Weight and Fibre Plug Weight

(Scaled Distance = 0.5 $ft/lb^{1/3}$, Ambient Pressure 1 Atmosphere)

Source	Nominal Charge Wt., lbs.	Plug Mass, grams: 17 - 19 $I/W^{1/3}$ psi-ms/$lb^{1/3}$	σ_1	N	30 - 35 $I/W^{1/3}$ psi-ms/$lb^{1/3}$	σ_1	N	50 - 60 $I/W^{1/3}$ psi-ms/$lb^{1/3}$	σ_1	N	Average over Plugs $I/W^{1/3}$ psi-ms/$lb^{1/3}$	σ_1	N	F Test at 1% level
New	1/4	720	21	11	719	17	11	762	14	5	727	24	27	Means Unequal
ERIM 1088	1/4				763	6	12							
All	1/4										738	27	39	Means Unequal
New	1/2	762	39	6	733	35	5	775	23	7	759	34	18	Means Unequal
ERIM 1088	1/2				823	12	19							
All											792	43	37	Means Unequal
New	1	755	27	7	765	34	8	808	21	5	772	29	20	Means Equal
ERIM 1088	1							774	15	6				
All	1										772	29	26	Means Equal
Average Over Chg. Weights														
New		741+	39	24	737	33	24 #	771+	25	17	750	35	65	Means Unequal
All					772	35	55 #	777+	22	22*				
New 1/2, All 1 lb.											$\boxed{767}$	33	44	Means Equal as 3 groups or 7

Boxed value taken as "best value"

+ means equal

means unequal

* one round discarded in mean or means

σ_1 = standard deviation of individual measurement in psi-ms/$lb^{1/3}$

N = number of measurements

TABLE II

Effect of Charge and Plug Masses and of Plate Size on Measured Normally Reflected Impulse, $I/W^{1/3}$, ($psi\text{-}ms/lb^{1/3}$) at 2.5 $ft/lb^{1/3}$ Ambient Pressure 1 Atmosphere

Plate Size and Thickness	Source	Nominal Charge Weight	Plug Mass, grams																Average Over Plugs		
			2 - 3				17 - 18				30 - 33				55 - 60						
			$I/W^{1/3}$	σ_i	N	$t_p/W^{1/3}$ $ms/lb^{1/3}$	$I/W^{1/3}$	σ_i	N	$t_p/W^{1/3}$ $ms/lb^{1/3}$	$I/W^{1/3}$	σ_i	N	$t_p/W^{1/3}$ $ms/lb^{1/3}$	$I/W^{1/3}$	σ_i	N	$t_p/W^{1/3}$ $ms/lb^{1/3}$	$I/W^{1/3}$	σ_i	N
Six ft. new equipment and 8 ft. (BRLM 1088) square plates 1" thick	New	1/8	69.3	7.6	5	1	48.9	5.5	12	11	41.5	1.9	6	20	35.1	2.2	5	50			
	New	1/4					53.1	3.9	5	6					44.3	5.2	6	22			
	1088	1/4									47.6	5.4	20	13							
	New	1/2	55.6	2.6	5	0.4	65.3	2.1	5	3					48.3	0.6	5	13			
	1088	1/2									53.0	3.2	17	8							
	New	1	68.6	4.0	5	0.3	66.1	3.6	10	2	63.5	3.7	5	3	66.8	0.8	5	6	63.2	6.0	51
	1088	1									60.9	6.5	26	3							
	1088	2									62.0	3.8	8	2							
	All	1 & 2																	63.1	5.8	59
	Average Over Charge Masses		64.5	8.1	15																
Five ft. dia. circular plate 0.75 inches thick	New	1/8	65.0	4.5	5	1									47.9	3.8	5	28			
	New	1	59.7	3.5	5	0.2									70.0	5.3	10	6			
Three ft. dia. circular plate	New	1/8	67.0	2.6	5	1									52.0	2.0	5	25			
	New	1	60.0	1.6	5	0.2									62.3	2.0	5	5			
	Average over chg masses & plate sizes		63.6	8.8	35	0.2	62.6	3.1	20	— 6	61.2	5.9	39	6	67.3	5.0	20	6	63.2	6.0	11
Three ft. dia. plate w/3" tube (not included in averages because of large standard deviation)	New	118	59.6	9.9	5	5									29.6	2.1	4	150			
	New	1	97.4	5.5	5	1									24.8	5.8	5	90			
Five ft. dia. plate w/3" tube (not included in Averages)	New	1/8	53.7	9.6	5	5															
	New	1	62.9	3.7	5	1															

Average omitted where data suggest trend.

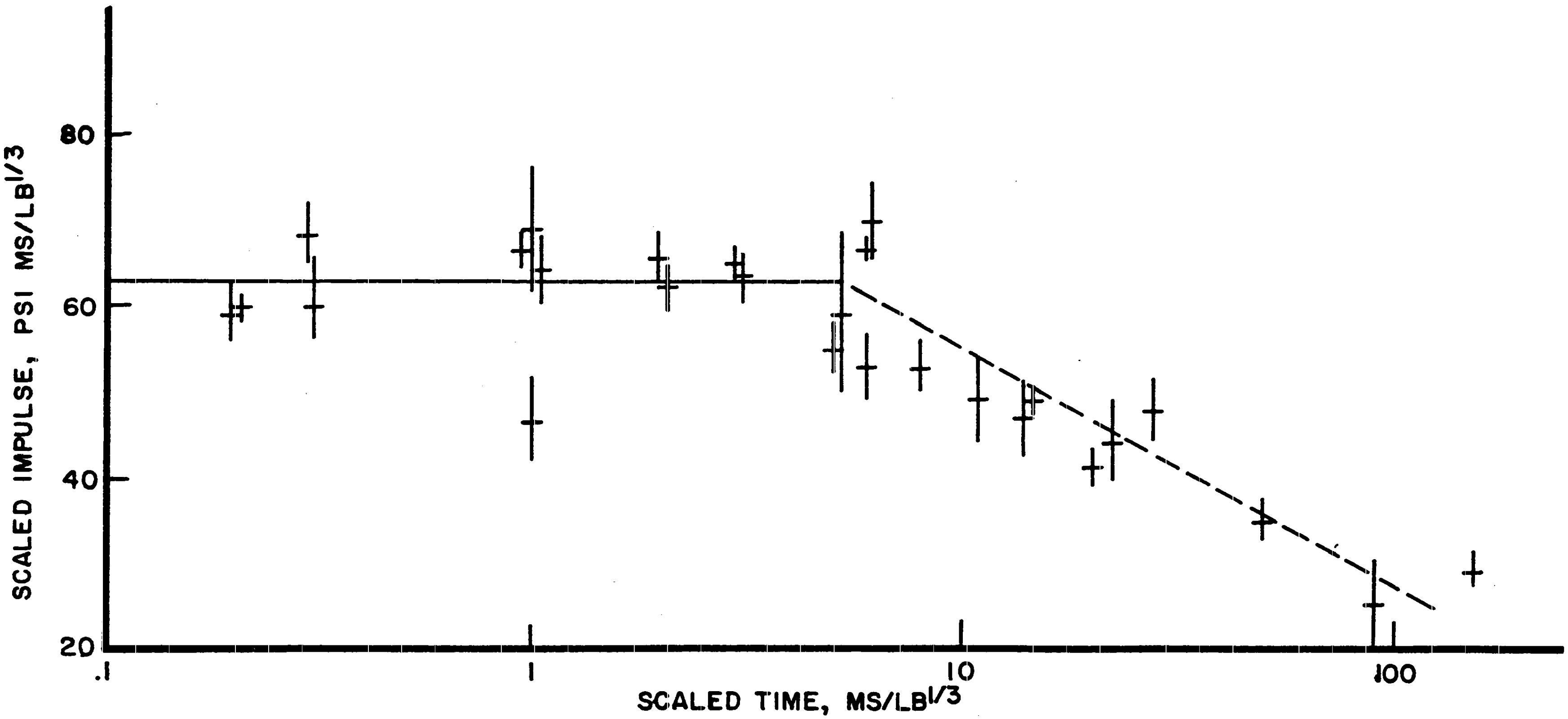
TABLE III

Sea Level Measurements of Normally Reflected Impulse at 3 ft/lb$^{1/3}$

Equipment	Charge Wt., lbs.	Plug Mass, Grams	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$t_p/W^{1/3}$ ms/lb$^{1/3}$
BRL Memo. 1241	1	17.4	46.6	5.1	15	
	1	31.5	37.2	2.3	5	
New	1/8	10.5	58.0	1.0	5	2.5*
	1/8	17 - 18	36.0	6.5	12	6
	1/4	17 - 18	37.6	4.4	5	5
	1/2	17 - 18	53.7	1.4	5	3
	1	17 - 18	54.4	1.0	5	2
Average of new data for $t_p \leq 5$**		17 - 18	55.4		15	

* 3/4" thick plate

** t_p is time (in milliseconds) for plug to move through plate thickness or tube attached to back of plate.



SCALED IMPULSE ($I/W^{1/3}$) VS. ESTIMATED SCALED TIME ($t_p/W^{1/3}$) FOR PASSAGE OF PLUG INTO FREE AIR

FIGURE I

plug weight is suitably adjusted to charge size. The difference between means found with 2-3 gram plugs probably results from weighing to 0.1 gram only. Also these plugs were of balsa wood and sometimes tumbled. The light plugs do show that even a one-eighth pound charge of Pentolite can be used if the plug weight is reduced to a suitable value. This is a great convenience at reduced pressures, permitting the use of smaller equipment and a smaller chamber.

Several plate sizes were used because diffraction is another possible cause of failure of Hopkinson scaling. No appreciable edge effects appeared. The size of the equipment will be reduced for increased portability. It is difficult to account for results at the 0.5 foot/pound$^{1/3}$ scaled distance. Measured impulse increases with both charge and plug weight. Table IV shows that it also depends on the material of the plug. All these effects are small, but because of the precision of the measurements at this distance are significant. In comparing the materials, similar rounds were fired alternately with fiber and with aluminum plugs. Reflected peak pressures at this scaled distance are in excess of 25,000 psi so that compression and distortion of the plug probably play a role in these anomalies. The shock velocity in the fiber is much less than in aluminum and damping greater so that it is possible that initial drag on the aluminum plug is greater, but this is entirely speculative.

Since results at reduced pressures are in accord with Hopkinson scaling except at the shortest scaled distance, ($Z = 0.5\ lb/W^{1/3}$) no similar study was made under high altitude conditions. Reflected peak pressure increases more than linearly with ambient pressure while normally reflected impulse is nearly independent of ambient pressure at small distances. Thus duration of the positive phase is longer at reduced pressure[8] and the negative phase has a greatly reduced effect upon the total impulse under similar experimental conditions.

RESULTS

Results of measurements are reported in Tables V and VI and shown in Figure 2. In spite of the large amount of work on the performance of the equipment, some unexplained discrepancies between the original results of

TABLE IV

Comparison of Aluminum 2024T4 and Fibre Plugs at $Z = 0.5$ ft/lb$^{1/3}$,

1/4 Pound Nominal Charge Weight

Aluminum Plug						Fibre Plug								
Plug Mass, grams	Ambient Conditions: P_o, atms.	Ambient Conditions: Alt. x 1000 ft.	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_1	N	Plug Mass, grams	Ambient Conditions: P_o, atms.	Ambient Conditions: Alt. x 1000 ft.	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_1	N	Mean $I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_1	N
20.3	1	0	682	17	5	17-18	1	0	720	21	11	708 Means Unequal	27	1[illegible]
36.4	1	0	674	27	5	30-31	1	0	719	17	11	70[illegible] Means Unequal	29	1[illegible]
36.4	0.736	10	651	29	5	17.5	.736	10	706	14	5	678 Means Unequal	36	10
36.4	0.53	20	649	7	5	17.9	.53	20	700	21	5	674 Means Unequal	31	10
36.4	0.263	32	679	24	5	18	.263	32	713	24	5	695 Means Unequal	29	10
Average	All		677 Means Equal	27	25				714 Means Equal	20	37			
Average	2 types		699	24	64									

TABLE V

Sea Level Normally Reflected Impulse (psi-ms/lb$^{1/3}$) Measurements at Distances Between 0.75 ft/lb$^{1/3}$ and 2.0 ft/lb$^{1/3}$

Source	Scaled Dist. ft/lb$^{1/3}$	Nom. Chg. Wt. lb.	$I/W^{1/3}$	σ_i	N	Remarks
1088		1/4	376.2	8.0	28	
Present		1/4	348.0	17.0	17	
1088	.75	1/2	382.2	12.7	26	Not averages of report, rounds
1088		1	364.1	14.4	19	discarded on basis of average over weights.
Present		1	348.7	6.9	5	
Average	.75	1/4-1	368.9	17.5	95	Means not equal
Present		1/8	192.2	7.1	3	Omitted in average
1088		1/4	221.8	8.7	20	
Present		1/4	225.2	16.5	4	
1088		1/2	234.7	4.4	19	
Present	1.00	1/2	231.3	20.3	6	
1088		1	229.0	13.3	23	
Unpub.		1	214.4	10.9	10	Modified equipment of BRLM 1241
Unpub.		1	238.1	6.4	7	Orig. equipment of BRLM 1241
1088		2	225.7	18.2	8	
Average		1/4-2	227.9	12.4	97	Means equal as 2 classes below but unequal as 8
1088 Av.	1.00	1/4-2	228.1	10.9	70	Means equal
New work	1.00	1/4-1	227.2	6.4	27	Means equal
1088		1/4	124.0	5.1	29	
Present		1/4	120.0	6.6	5	
1088	1.50	1/2	130.9	5.0	32	
Present		1/2	128.9	7.6	9	
1088		1	135.7	6.8	42	
Present		1	132.0	6.1	5	
Average	1.50	1/4-1	130.4	7.2	122	Means unequal as six classes or 3
Average	1.50	1/2-1	133.0	6.7	88	Means unequal as four classes or 2
1088 Av.	1.50	1/4-1	130.9	7.5	103	Means unequal
Average	1.50	1	135.3	6.8	47	
Present		1/8	77.6	-	2	
Unpub.		1/4	74.2	3.2	13	Orig. equipment of 1241, 31 g plug, 7 rounds
Present		1/4	87.9	6.5	5	
1088	2.00	1/2	79.6	5.1	12	
Present		1/2	88.0	-	1	
1088		1	87.2	4.2	8	
Unpub.		1	85.6	4.3	18	Modified equip. of 1241, 17 g plug 10 rounds
Unpub.		1	84.7	5.9	12	Orig. equipment of 1241
Average Omitting First Two sets	2.00	1/4-1	84.6	5.6	56	Means equal

TABLE VI

Normally Reflected Positive Impulse as a Function of Scaled Distance and Ambient Pressure

Ambient Press. p_o, atmos.	1.00			0.737			0.526			0.263			0.132			0.0526			0.0270			0.010[illegible]			0.00595					
Alt., 1000 ft.	0			10			20			32.5			47.[illegible]			66			80			100			125			Limiting Average		
Scaled Distance Z, ft/lb$^{1/3}$	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N	$I/W^{1/3}$ psi-ms/lb$^{1/3}$	σ_i	N
0.5	767	33	44							733	32	7				739	21	9				734	21	4	712	14	5	730	23	18
0.75	369	16	95	331	24	5	346	30	10	346	30	10	322.2	4.4	5	322	12	5	305.2	9.2	9	342	11	[illegible]	320.[illegible]	4.6	5	320	1[illegible]	29
1.0	228	12	97	203	16	10	202	11	5	200	11	7	186.7	5.1	5	187.5	6.4	26	186.9	2.0	3	190.1	4.4	9				187.9	5.7	4[illegible]
1.5	135.3	6.8	47	114	10	7	102	10	10	106.7	4.0	5	88.8	5.4	5	90.9	6.4	5	90.5	1.4	5	87.0	2.6	5				89.3	4.4	20
2.0	84.6	5.6	56	78.4	4.0	5	68.9	3.2	5	66.5	9.6	17	52.5	4.9	10	58.1	4.2	10	51.8	3.5	4	58.1	4.2	8				55.6	5.1	52
2.5	63.7	6.1	109																											
3.0	35.4	2.1	15							41.1	2.1	5	34.3	2.5	5	26.7	7.8	8	25.5	2.5	11	21.3	3.4	8	21.6	1.2	5	21.4	2.9	13

Values from 1/4 lb. charges at Z = 0.5 ft/lb$^{1/3}$ and other values believed affected by the failure of Hopkinson Scaling omitted.

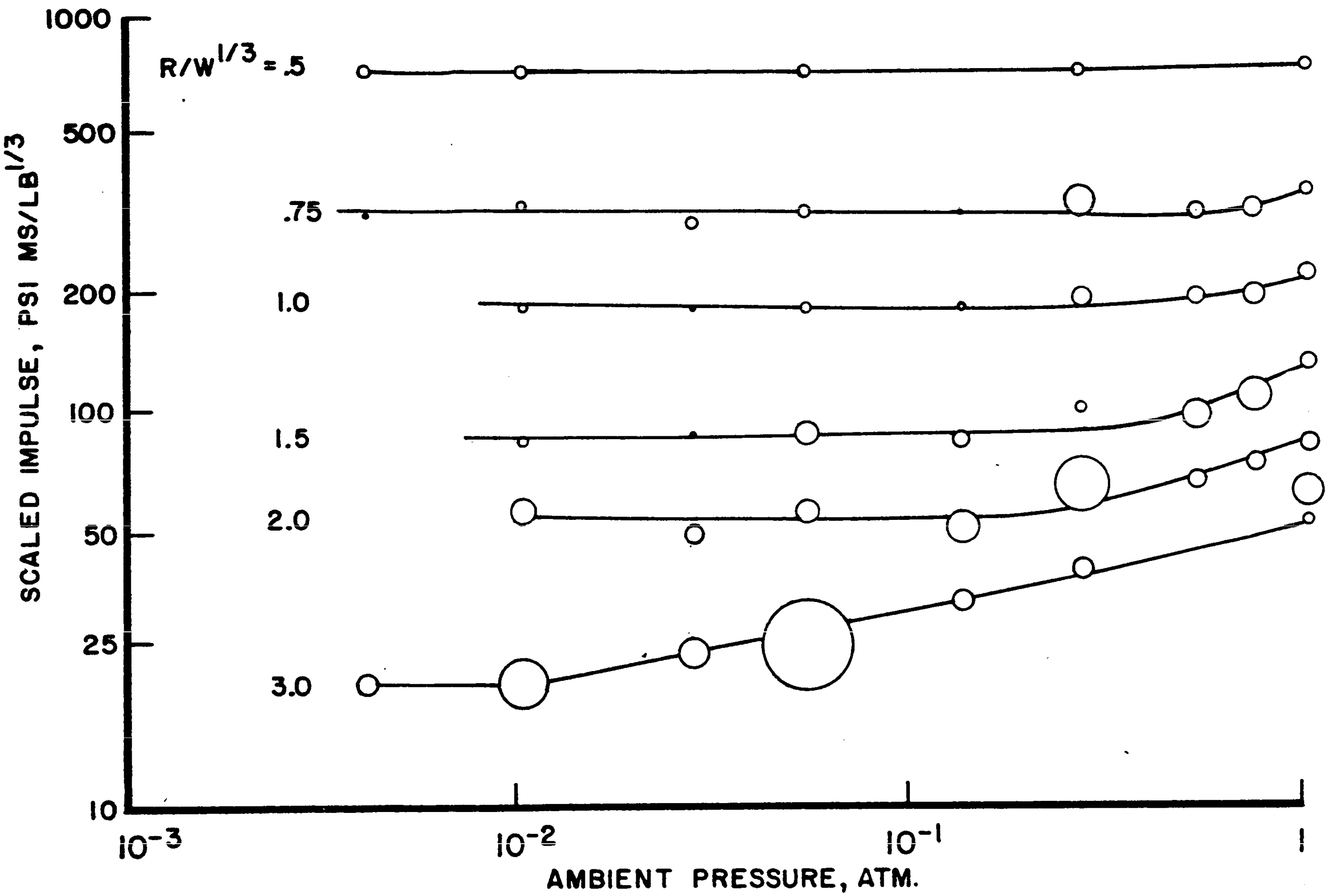
Limiting average as p_o 0 independent of p_o except at Z = 0.75 ft/lb$^{1/3}$. (F test)

Johnson, Patterson, Olson and these remain. Therefore, the choice of "best value" for the scaled impulse at sea level is to some extent subjective. Lacking a method of determining possible sources of error in previously completed work, reconciliation is no longer possible and the newer work, resulting from more detailed checks and on greater experience of operating personnel, has been preferred. The differences in the results are small and do not affect the general conclusions. In some instances, theoretical conclusions given in the section on Interpretation of Results were given some weight. There are no significant discrepancies between the new results and those of Olson, Patterson and Williams.[2] The statistical treatment, discussed in the next section, causes the differences in conclusions as to equality of means.

The striking feature of the results is the small change in normally reflected impulse with ambient pressure shown in Table VI and Figure 2.

STATISTICAL TREATMENT OF THE DATA

As far as possible the methods of references (1) and (2) have been used. An F test appears unsuited to comparing groups of measurements of varying standard deviations, particularly when a Student's t test at a different level has been applied to selecting measurements within groups. Unfortunately the F test was incorrectly made in reference (1). Even when the rejection of measurements is based on the mean of all groups, as with the sea level measurements here but not in that report, means obtained with different charge weights are unequal at the 1% level at scaled distances of 0.5, 0.75 and 1.5 as well as 2.5 feet/pounds$^{1/3}$. However, it is clear in looking at the data of that report that variations of impulse with charge weight are random, showing no trend except at 2.5 feet/pounds$^{1/3}$. The F test apparently gives reasonable results only when applied to larger groups of these measurements, probably because the condition of equal distributions of errors is not met within a smaller group.



NORMALLY REFLECTED POSITIVE IMPULSE AS A FUNCTION OF SCALED DISTANCE ($R/W^{1/3}$) AND AMBIENT PRESSURE P_0

FIGURE 2

Measurements were rejected on the basis of the mean from all charge weights but not on the basis of the mean from the different ambient pressures because Hopkinson scaling was assumed a priori, while there is no reason to expect reflected impulse to be independent of altitude except as noted in the data of reference (2) and that presented in this work.

SOURCES OF ERROR

The larger standard deviations of measurements at intermediate pressures probably results from errors in measurement of ambient pressure. In the cylindrical chamber mercury manometers are used, open-end for higher and closed-end for lower pressures. The manometers are at some distance from the chamber and connected to its wall by one-fourth inch copper tubing. Errors are introduced by the difficulty of reading the manometer and by inequalities in pressure caused by slight leaks in the chamber. At low ambient pressure, impulse is nearly unaffected by these errors. In the blast sphere, a more accurate aneroid pressure gage is used so that measurements at 3 feet/pounds$^{1/3}$ do not show this dependence of uncertainty on ambient pressure. The relatively poor precision of measurements at this distance results from the large gravitational correction, which makes the percentage error in impulse twice that in velocity. A lighter plug would probably increase their precision.

INTERPRETATION OF RESULTS

Olson, Patterson, and Williams[2] concluded from their data that Sachs's scaling was applicable. Goodman[5] combined their altitude measurements with those made from pressure-time histories at greater distances using Sachs's scaling and found no conflict. This agreement is fortuitous and results from the low ambient pressures and restricted distance range of data in reference (2). The impulse drops, at small distances, approximately as the reciprocal of the square of the distance. In Sachs's scaling, for this distance relation,

$$(1)\quad I/(p_o{}^{2/3}W^{1/3}) = C\, W^{2/3}/(R^2 p_o{}^{2/3})$$

or

$$(1a)\quad I = CW/R^2$$

where I is the impulse, p_o the ambient pressure, W the charge mass, and C a constant. Thus Sachs's scaling predicts, for this variation of impulse with distance from the charge, that the impulse is independent of ambient pressure. Since the latter statement is correct at low ambient pressures, the conclusion of reference (2) does not conflict with their data. However, extension of their work suggests another interpretation.

The variation of positive impulse approximately with the inverse square of the distance, with its independence of ambient pressure at low pressures, suggests that the measured impulse is the impulse of flow of the explosion gases. This interpretation could be checked directly by measurements of total impulse. Interchange of shock impulse with ambient air vanishes as the ambient pressure decreases. Thus, the limiting total impulse of flow at low ambient pressures decreases inversely as the square of the distance from the charge. In general, the total radial impulse of flow increases at the rate $\rho_o uU$ or $P-p_o$, where ρ_o is the density of the ambient air, u the material and U shock velocity, $P-p_o$ is the peak overpressure. The total flow impulse per unit area is

$$(2)\quad I_t = I_o + \frac{1}{R^2} \int_o^{T(R)} r^2 (P-p_o) \; dt = I_o + \Delta I_F/4\pi R^2$$

The integral was evaluated for p_o = 1 atmosphere by the Computing Laboratory from the smoothed compiled data of Goodman. I_t and I_o are the total scaled impulse at scaled distance Z and at shock formation, which is assumed to be at the charge surface. R is the distance of the front from the charge center at time T(R) and r is the distance from the charge center. In Table VII, I_oR^2 is given as computed from equation (2) and the measured impulse, I_m, assuming that P/p_o is independent of p_o. I_o, thus computed, is seen to be constant and equal to the value of I_m at low ambient pressures at distances less than 2 feet/pounds$^{1/3}$. We therefore add the following hypothesis: interchange of impulse between positive and negative phases is small out to a distance of 1.5 foot/pound$^{1/3}$ (11 charge radii). At greater distances and one atmosphere ambient pressure, the same computation gives much lower values of I_oR^2 indicating that the negative phase has an appreciable and rapidly increasing influence on normally reflected positive impulse as the shock moves to distances beyond 10 charge radii. In Brode's[7] computations, this is near the shortest distance at which the particle velocity does not increase

TABLE VII

Initial Impulse of Flow per Steradian Pound from Equation (2) and Table VI

Impulse of Flow, psi-ms ft^2/lb		Ambient Conditions p_o atms.	Scaled Distance Z, ft/lb$^{1/3}$ .5	.75	1	1.5	2	2.5	3	Means	F Test, means over [illegible]
$\Delta I_F/4\pi W$		1.0	9.08	23.6	46.8	119.9	216.2	351.7	479.1		
$(I_m R^2 - \Delta I_F/4\pi)/W$		1.0	182.6	184.0	181.0	185.0	122.0	44.0	7.0	183.0	equal
	σ_1		8.2	9.0	12.0	15.0	22.0	46.0	13.0	11.0	
	N		44	95	97	47	56	51	51	283	
$(I_m R^2 - 0.737\ \Delta I_F/4\pi)/W$		0.737	(169.0)	168.8	178.0	168.0	155.0			173.0	equal
	σ_1		13.5	10.0	22.0	16.0				15.0	
	N		5	10	7	5				22	
$(I_m R^2 - 0.526\ \Delta I_F/4\pi)/W$		0.526	(168.0)	169.1	177.6	166.4	162.0			170.0	equal
	σ_1			7.9	11.0	22.0	13.0			17.0	
	N			5	5	10	5			20	
$(I_m R^2 - 0.263\ \Delta I_F/4\pi)/W$		0.263	180.9	188.0	188.0	208.6				190.0	unequal
	σ_1		8.0	17.0	11.0	9.0				15.0	
	N		7	10	7	5				29	
$(I_m R^2 - 0.132\ \Delta I_F/4\pi)/W$		0.132	(175.0)	178.1	180.5	184.0	182.0		277.0	180.9	equal
	σ_1			2.5	5.1	14.0	20.0		22.0	4.8	
	N			5	5	5	10		5	15	
$(I_m R^2 - 0.053\ \Delta I_F/4\pi)/W$		0.053	183.6	179.9	185.0	198.2	221.0		212.0	185.6	equal
	σ_1		5.2	6.8	6.4	14.0	17.0		20.0	8.6	
	N		9	5	26	5	10		8	45	
$(I_m R^2 - 0.027\ \Delta I_F/4\pi)W$		0.027	(172.0)	171.1	185.6	200.4	201.0		217.0	182.0	unequal
	σ_1			5.2	6.4	3.2	14.0		21.0	14.0	
	N			9	26	5	4		11	17	
$(I_m R^2 - 0.0105\ \Delta I_F/4\pi)W$		0.0105	183.3	192.3	189.9	195.0	230.0		187.0	190.3	equal
	σ_1		5.2	6.2	4.4	16.0	17.0		14.0	8.8	
	N		4	5	9	5	8		8	23	
$(I_m R^2 - 0.0039\ \Delta I_F/4\pi)W$		0.0039	177.9	180.2					192.0	179.0	equal
	σ_1		3.5	2.6					11.0	3.2	
	N		5	5					5	10	
Means over p_o			182.3	182.0	182.0	185.0				183.0	equal
	σ_1		6.5	11.0	11.0	19.0				14.0	
	N		69	44	167	89				464	
F Test, means over p_o			equal	unequal	unequal	equal				unequal	

Values in parentheses omitted in averages as deviating from Hopkinson scaling.

discontinuously with time and a negative pressure phase precedes the arrival of the second shock. The value of $\dot{I}_o R^2$, however, is much higher than would be expected from Taylor's[9] work on which Brode's is based.

New computations of detonation conditions in Pentolite have been made by Ralph Shear of these Laboratories[10]. Shear computed for the authors the value of the integral

$$\int_0^1 \rho\, u\left(\frac{r}{R}\right)^2 d\left(\frac{r}{R}\right) = 3.924 \text{ g/(cm}^2\text{s)}$$

where ρ = density, u mass velocity, in the detonation products. Changing to the units in which the measurements are reported and multiplying by the charge radius cubed per pound, the total impulse per steradian pound is 40.2 psi. ft^2 s/lb. The total impulse per unit weight is the mass average velocity, 713 m/s, or 0.39 the mass velocity behind the detonation front. This computed value is reasonable. The measurements indicate that the initial first positive impulse is 4.5 times the total impulse of flow. Negative impulse of flow is more than three times the total impulse, since the addition of impulse of flow after shock formation has been taken into account in the computation of I_o from the measurements. Static impulse can be neglected at the distances in question (Figure 2, Reference 5). Observation of negative impulse of flow presents difficulties and requires new equipment. Attempts at measurement with simple equipment are planned.

CONCLUSIONS

Measurements of reflected positive impulse which agree with Hopkinson scaling can be made by careful control of the time of measurement. This impulse is nearly independent of ambient pressure at small distances ($Z < 1.5$ ft/lb$^{1/3}$) from the charge.

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The study indicates that at small distances ($Z < 1.5$ ft/lb$^{1/3}$) the change in normally reflected impulse with variation in ambient pressure is negligible; it further suggests that the measured impulse, within several charge radii, of the explosive is due to the flow of the explosion gases and that the interchange of impulse between positive and negative phases is small.

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